



Nuclear Power  
And  
Proliferation Resistance:  
Securing Benefits, Limiting Risk

A report by the  
Nuclear Energy Study Group  
of the American Physical Society Panel on Public Affairs

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*PANEL ON PUBLIC AFFAIRS*

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*THE NUCLEAR ENERGY STUDY GROUP*

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The Nuclear Energy Study Group is composed of a broad range of experts. Together, they have considerable expertise in safeguards, nuclear-fuel cycle technologies, non-proliferation policy, international cooperation on nonproliferation R&D, and the management of federal nuclear technology programs.

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# Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risk

“Nuclear proliferation is a significant threat to America’s security. We need to more consistently prevent the emergence of new nuclear weapons states, and to keep nuclear weapons capability out of terrorist hands. A comprehensive policy approach must address the many pathways that states or non-state actors may use to acquire nuclear weapons capabilities.”

-- *House Policy Subcommittee on National Security & Foreign Affairs, January 2005*

## Summary and Key Recommendations

### **Benefit: Meeting the Global Energy Demand**

Global electricity demand is expected to increase by more than 50 percent by 2025. Nuclear power is a primary carbon-free energy source for meeting this extensive global energy expansion.

### **Risk: Proliferation and Nuclear Weapons**

The technologies used in peaceful nuclear power programs overlap with those used in the production of fissionable material for nuclear weapons.

The elements of a nuclear power system include: facilities that mine and mill uranium ore, facilities that enrich uranium to create fuel, fuel fabrication facilities, reactors that burn that fuel to generate electricity, possibly facilities to reprocess the spent fuel, and waste storage sites.

Nuclear reactors themselves are not the primary proliferation risk; the principal concern is that countries with the intent to proliferate can covertly use the associated enrichment or reprocessing plants to produce the essential material for a nuclear explosive. Further, poorly secured nuclear materials present a risk of proliferation through theft and transfer to a country or terrorist groups.

## **Securing Benefits, Limiting Risk**

The extent to which nuclear power will be an acceptable option to meeting future global energy requirements will depend upon its cost, safety, waste management, and the associated proliferation risks. While all these issues are important considerations, this report exclusively examines options for limiting proliferation risks.

No single diplomatic, military, economic, institutional, or technical initiative alone will be able to fully deal with this proliferation challenge. The best prospect for achieving non-proliferation goals while expanding nuclear power is to engage all appropriate means.

While nuclear power cannot be made “proliferation proof”, this report examines technological steps that the US can take to enhance the resistance of nuclear power systems to theft, diversion and breakout. These technical steps will be most effective when coupled with changes in institutional arrangements.

Specifically, the US should:

### **General Recommendations**

1. Significantly strengthen the federal Technical Safeguards R&D program: increase resources, identify near-term technology goals, formulate a technology roadmap, and improve interagency coordination.
2. Increase the priority of proliferation resistance in design and development of all future nuclear energy systems.
3. Develop & strengthen international collaborations on key proliferation-resistant technologies.
4. Align federal programs to reflect the fact that there is no urgent need to initiate reprocessing or to develop additional spent fuel repositories in the US.

*Detailed Recommendations on pages: 13, 16, and 22.*

## National Security & Proliferation Resistance

Worldwide, thirty new nuclear plants were under construction in March 2005, with 20 new plants in Asia alone. In addition to China's plan to greatly expand its nuclear power program, Indonesia, Vietnam and Egypt have all declared an interest in building their first civilian nuclear power plants.

As evidenced by the current situation in Iran, technological advances and institutional changes are required to avoid proliferation by countries taking advantage of a global spread of nuclear power. Consequently, whether or not the United States constructs new nuclear power plants over the next quarter century, it is vital to US national security that the US remain engaged in the development of proliferation-resistant nuclear-energy technologies and of technologies that can support new international arrangements to safeguard and coordinate future fuel-cycle deployment.

Report Structure	
Section I	Overview of the benefits of nuclear power, the associated proliferation risks, and the need for action.
Section II	Summary of the primary federal R&D programs focused on strengthening proliferation-resistance of nuclear power.
Section III	Examination of the Technical Safeguards program. Recommendations that could enhance the proliferation resistance of nuclear power <b>within 5 years</b> .
Section IV	Examination of nuclear systems design and development programs. Recommendations that could enhance the proliferation resistance of nuclear power <b>over the next 10 to 30 years</b> .



# Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risk

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## Section I

# Overview

### **Goal: Secure the Benefits, Limit the Risk**

The extent to which nuclear power will be a broadly accepted option for meeting future global energy needs depends upon cost, safety, waste management and the ability to limit the associated proliferation risks. While all four considerations are important, this report exclusively examines proliferation risks.

In particular, this report examines technical options that, taken together, can reduce the likelihood that a global expansion of nuclear energy would contribute to increased nuclear weapon proliferation. These technical options will be most effective when coupled with changes in institutional arrangements.

### **Nuclear Power and the Global Energy Future**

Current global annual electricity consumption is roughly 15 trillion kilowatt-hours. Demand is growing rapidly and the Department of Energy projects that global annual consumption will exceed 23 trillion kilowatt hours by the year 2025.<sup>1</sup>

Numerous energy sources are available to satisfy this growing electricity demand including coal, natural gas, and nuclear power as well as renewable sources such as hydropower, biomass and wind. However, renewable energy sources offer only limited possibilities for achieving significant energy growth in the near term.<sup>2</sup> Domestic resources of natural gas have shown considerable price volatility, and international markets for natural gas are still in the early stages of development. Consequently, coal and nuclear power will be primary sources for many countries that are appreciably expanding their energy supply.

The coal option currently entails significant environmental costs such as those associated with carbon dioxide and particulate emissions, including possibly substantial changes in global climate with uncertain consequences.<sup>3</sup>

Nuclear power now meets roughly 17% of the global electricity demand and could make a significant contribution to carbon-free energy expansion.<sup>4</sup> Thirty nuclear plants were under construction in March 2005, with 20 new plants in Asia alone.<sup>5</sup>

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<sup>1</sup> Department of Energy, Energy Information Administration: <http://www.eia.doe.gov/oiaf/ieo/pdf/tbl14.pdf>

<sup>2</sup> "Ending the Energy Stalemate," National Commission on Energy Policy, December 2004, p vii:

<http://www.energycommission.org>

<sup>3</sup> This problem would be ameliorated if technology can be developed to economically capture and sequester the carbon dioxide.

<sup>4</sup> "The Future of Nuclear Power: An Interdisciplinary MIT Study," <http://web.mit.edu/nuclearpower/>

<sup>5</sup> Nuclear Threat Initiative, <http://www.nti.org/db/china/pwrretr.htm>

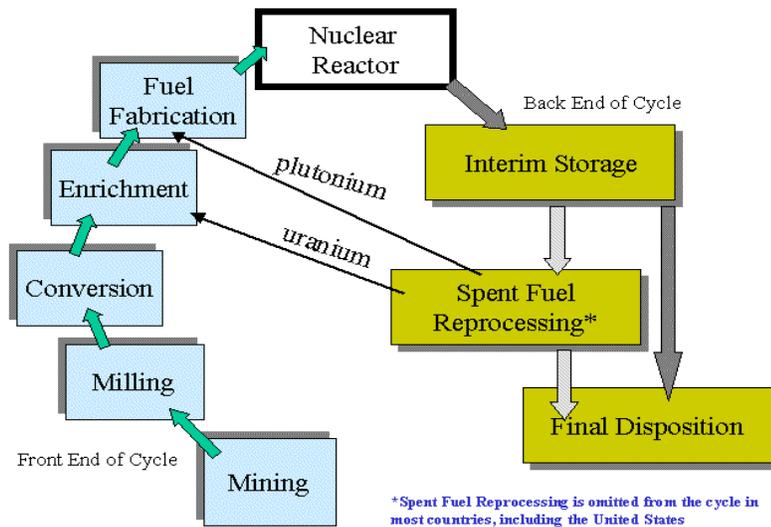
Given nuclear power’s potential to reduce the dependence on fossil fuels, a balanced U.S. energy policy must keep open the nuclear energy option through the development and availability of nuclear plants and supporting infrastructure that can be built, operated, and eventually decommissioned in a safe, secure, environmentally sound and cost-effective manner.

**Nuclear Power, Nuclear Proliferation and National Security**

The technologies and materials used in the manufacture of nuclear weapons overlap with those used in peaceful nuclear power applications. The extent to which nuclear power will be an acceptable and enduring option to meeting future energy requirements in many regions of the world will therefore depend in part upon the ability to minimize the associated proliferation risks.

The elements of a nuclear power system include: facilities that mine and mill uranium ore, facilities that enrich uranium to create fuel, fuel fabrication facilities, reactors that burn that fuel to generate electricity, possibly facilities to reprocess the spent fuel,<sup>6</sup> and waste storage sites.

**Elements of a Nuclear Power System (Fig 1)**



Nuclear reactors themselves are not the primary proliferation risk. The principal proliferation concern among the various elements of a nuclear power system are the enrichment and reprocessing facilities, which can produce materials directly usable in weapons. In addition, the spent fuel is a potential source of plutonium that must be safeguarded to prevent its clandestine separation for use in weapons, and fresh low-enriched uranium (LEU) fuel materials are a potential source for clandestine enrichment to nuclear weapons grade material. Further, poorly secured nuclear

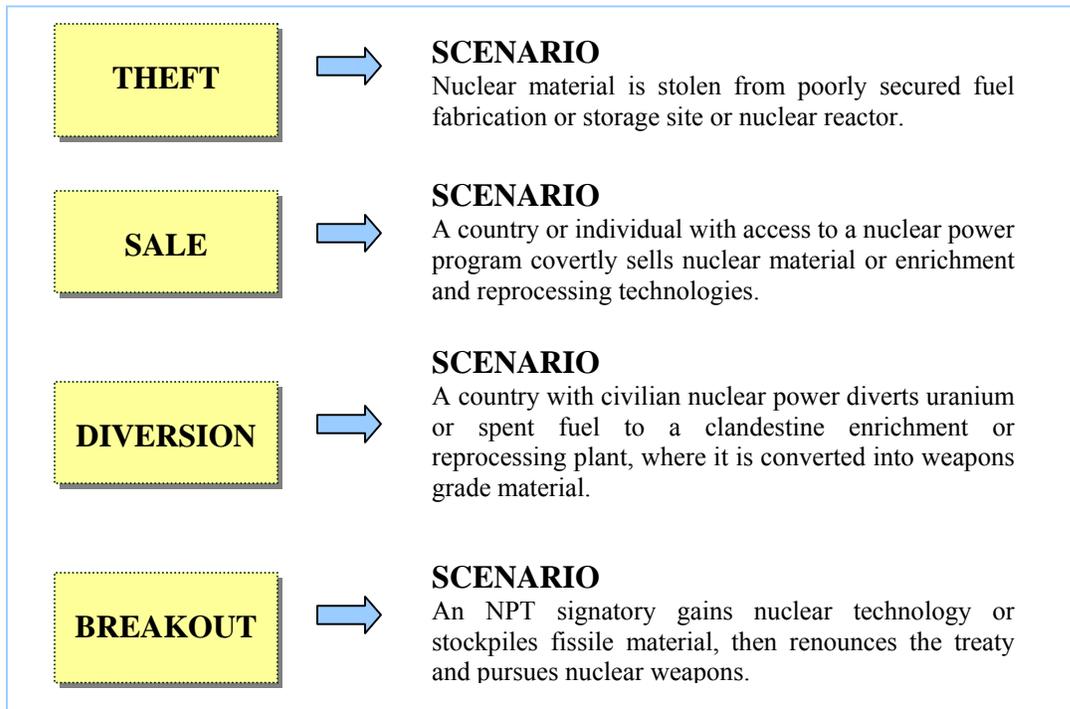
<sup>6</sup> “Reprocessing” is the term used for the chemical operations carried out to separate the fission products from the spent fuel and to separate and purify the uranium and plutonium.

materials, including plutonium separated for fabrication into reactor fuel, present a risk of proliferation through theft and transfer to another country or terrorist group.

The challenges to the non-proliferation regime are evident worldwide. Negotiations are under way to persuade Iran to abandon a uranium enrichment program, heavy water production plant and high-power research reactor that Iran claims are for civilian use but could easily be used to produce high-enriched uranium and plutonium for nuclear weapons. In North Korea, negotiations continue on termination of its nuclear weapons program and the associated reprocessing and enrichment activities. Much of Russia's approximately 2 million pounds of weapons usable uranium and plutonium from both military and civilian nuclear energy programs may not be satisfactorily secured.<sup>7</sup> Also, the smuggling network run by A.Q. Khan, who in the 1970s diverted uranium enrichment technology from a European consortium for use in Pakistan's nuclear weapons program, reportedly sold enrichment technology to several countries, including Libya.

This recent history leaves little doubt that civilian nuclear technology and materials can be misused, sold, stolen, or used as a cover for development of a nuclear weapons production capability. Figure 2 illustrates four primary pathways from nuclear-power programs to nuclear-weapons proliferation: *theft*, *sale*, *diversion*, and *breakout*.<sup>8</sup>

### Pathways: From Nuclear Power to Nuclear Weapons (Fig 2)



<sup>7</sup> "Controlling nuclear warheads and materials", Harvard, Project on Managing the Atom, available at: [http://www.nti.org/e\\_research/cnwm/overview/cnwm\\_home.asp](http://www.nti.org/e_research/cnwm/overview/cnwm_home.asp)

<sup>8</sup> For an overview of the technical issues see: <http://www.ne.doe.gov/nerac/FinalTOPSRpt.pdf>

## Addressing the Proliferation Risks of Nuclear Power

There are a number of diplomatic, economic, military, and scientific and technical (S&T) approaches to reducing the proliferation risks of nuclear power.<sup>9</sup>

President Bush made a two part proposal to restrict the spread of enrichment and reprocessing technologies: 1) the world's leading nuclear exporters should ensure that states have reliable access at reasonable cost to fuel for civilian reactors, so long as those states renounce enrichment and reprocessing; and 2) The 40 nations of the Nuclear Suppliers Group should refuse to sell enrichment and reprocessing equipment and technologies to any state that does not already possess full-scale, functioning enrichment and reprocessing plants.<sup>10</sup> IAEA director, Mohammed ElBaradei proposed a 5-year moratorium on construction of new enrichment or reprocessing plants while an effort is made to establish a multi-national alternative to nationally owned plants.<sup>11</sup>

Such fuel assurances and pledges to restrict sales are important components of a strategy to reduce the proliferation risks of nuclear power.<sup>12</sup> However, no single diplomatic, military, economic, or technical initiative alone will be able to fully deal with the proliferation challenge. The best prospect for achieving non-proliferation goals while expanding nuclear power is to engage all appropriate means and to maximize their respective contributions.<sup>13</sup>

From a technical point of view, nuclear power cannot be made “proliferation proof”. However, numerous steps can be taken -- and must be taken -- to make it as “proliferation-resistant” as reasonably possible.

This is an urgent global security problem. China is poised to greatly expand its nuclear power program and Indonesia, Vietnam and Egypt have all declared an interest in building civilian nuclear power plants. Without technological advances and institutional changes, it will be easier for countries motivated to proliferate to take advantage of the global expansion of nuclear power or for terrorists to access nuclear materials. Iran's developing nuclear program indicates the urgent need to enhance the proliferation resistance of nuclear power.

Thus, whether or not the United States constructs new nuclear power plants over the next quarter century, it is vital to US national security that the US remain engaged in the development of proliferation-resistant nuclear-energy technologies and of technologies that can support any new arrangements to safeguard and internationalize the fuel-cycle and strengthen international institutions.

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<sup>9</sup> “Addressing the Challenge,” <http://www.iaea.org/NewsCenter/Statements/DDGs/2003/goldschmidt26112003.html>

<sup>10</sup> President Bush, February 11, 2004: <http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html>

<sup>11</sup> IAEA, 2005: [http://www.iaea.org/NewsCenter/News/2005/npt\\_2005.html](http://www.iaea.org/NewsCenter/News/2005/npt_2005.html)

<sup>12</sup> “Making the World Safe for Nuclear Energy,” J Deutch, A Kanter, E Moniz, D Poneman, *Survival*, Vol. 46, No. 4, pp. 65-80: <http://mit.edu/chemistry/deutch/policy/67MakingtheWorld2004.pdf>

<sup>13</sup> “Options for Strengthening the Global Nuclear Nonproliferation Regime,” Bengelsdorf, McGoldrick and Associates.

## Section II

# U.S. Proliferation-Resistance R&D Programs

There are four primary federal research and development (R&D) programs addressing proliferation resistance of nuclear power. There is considerable history behind the programs; this section provides only summaries.

The programs are located in the State Department and in the Department of Energy's Office of Nuclear Energy Science and Technology (DOE-NE) and National Nuclear Security Administration (NNSA). The budgets listed in Figure 3 are approximate.

### **Technical Safeguards**

The goal of Safeguards R&D is to develop technologies that deter and detect theft and diversion and to provide early and clear indication of breakout. Such technologies are aimed at facility design verification, material control and accounting, nuclear material measurements, process monitoring and surveillance, environmental sampling, and remote monitoring.<sup>14</sup>

### **Proliferation Resistance & Physical Protection (PR&PP)**

The goal of the PR&PP assessment program is to develop criteria to evaluate and compare proliferation resistance and physical protection of future nuclear energy systems, including reactors and their associated fuel cycle facilities.<sup>15</sup>

### **Generation Four Nuclear Energy Systems Initiative (Gen IV)**

The goal of Gen IV is to “develop and demonstrate advanced nuclear energy systems that meet future needs for safe, sustainable, environmentally responsible, economical, proliferation-resistant and physically secure energy.”<sup>16</sup>

### **The Advanced Fuel Cycle Initiative (AFCI)**

The mission of the AFCI is to develop proliferation-resistant spent nuclear fuel treatment and transmutation technologies in order to enable a transition from the current once-through nuclear fuel cycle to a future sustainable, closed nuclear fuel cycle. This includes the development of advanced reprocessing technologies.<sup>17</sup>

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<sup>14</sup> International Atomic Energy Agency: [http://www.iaea.org/Publications/Factsheets/English/S1\\_Safeguards.pdf](http://www.iaea.org/Publications/Factsheets/English/S1_Safeguards.pdf)

<sup>15</sup> Department of Energy: <http://www.ne.doe.gov/infosheets/PRPPMay2004.pdf>

<sup>16</sup> Department of Energy: <http://gen-iv.ne.doe.gov/>

<sup>17</sup> Department of Energy: <http://www.ne.doe.gov/infosheets/afci.pdf>

### U.S. Proliferation-Resistance R&D Budgets in millions (Fig 3)

	FY '05
Technical Safeguards R&D (State Department, DOE-NE, NNSA)	less than \$5 million <sup>18</sup>
PR & PP Assessment (DOE-NE, NNSA)	less than \$1 million
AFCI (DOE-NE)	\$68 million
Gen IV (DOE-NE)	\$40 million

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<sup>18</sup> The *total* safeguards budget is much larger than \$5 million and includes both domestic and international programs that largely implement or transfer technologies that are the result of R&D carried out 10 to 20 years ago.

## Section III

# Near-Term Approaches for Enhancing Proliferation Resistance: Technical Safeguards R&D

The current Safeguards program largely implements or transfers technologies that are the result of R&D carried out 10-20 years ago. Revitalizing Safeguards R&D is the most significant technical investment that can enhance the proliferation resistance of nuclear power within the next five years. The following section provides an overview of Safeguards and makes recommendations to strengthen and broaden the near-term impact of the federal Technical Safeguards program.

### **Safeguard Fundamentals**

International Safeguards are a set of activities that the International Atomic Energy Agency (IAEA) uses to verify that a country is adhering to international commitments not to use its nuclear program for nuclear weapons purposes.

The safeguards system is based on regularly verifying the accuracy and completeness of a country's declarations to the IAEA concerning nuclear-related activities and seeking to assure that no undeclared nuclear materials or activities exist within the country. In total, more than 900 declared facilities in 71 countries are "safeguarded" and subject to inspection.<sup>19</sup>

Domestic Safeguards and security refer to measures taken by national authorities to protect and account for their nuclear materials holdings.

Technical Safeguards refers to the technologies used both in domestic and international safeguards to protect nuclear material facilities from theft and to verify that the material and facilities are being used exclusively for peaceful purposes.

Safeguards technologies cannot prevent proliferation. Their primary contribution is in establishing barriers that make *theft* and *diversion* more difficult and detectable and provide early and unambiguous warning. Thus, they provide assurances to both national regulators and international authorities that facilities and materials are protected against both national and sub-national threats.

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<sup>19</sup> International Atomic Energy Agency: [http://www.iaea.org/Publications/Factsheets/English/S1\\_Safeguards.pdf](http://www.iaea.org/Publications/Factsheets/English/S1_Safeguards.pdf)

Safeguards also serve as confidence-building measures for countries to reassure their neighbors and the international community that they are in compliance with nonproliferation obligations. And, they are designed to provide the international community timely warning to intervene should a country be in breach of its commitments.

Consequently, technical safeguards complement diplomatic and legal efforts to restrain proliferation. Where institutional arrangements help to guide nations along peaceful nuclear pursuits, technical safeguards provide reassurance that their pursuits remain peaceful.

### **Investing in Safeguards R&D**

Domestic and international safeguards have always relied heavily on technology. Although the need to protect and control nuclear materials, technologies, and facilities was recognized from the days of the Manhattan Project, during the mid-1960's to mid 1970's the US significantly expanded its R&D programs designed to improve nuclear materials security and international safeguards. During this period the Department of Energy and its predecessor organizations (AEC and ERDA) managed substantial technology development programs focused on improving technical safeguards. During this very active period of safeguards R&D, many of the technologies used globally today by the IAEA were developed.

There has been a long-standing recognition that having an application-oriented safeguard technology base directed to long-term capability improvement is essential to making meaningful progress in mission performance. In addition, the US has recognized the value in investing in the widespread application of technical safeguards, for example spending more than \$1 billion through the Nunn-Lugar Program to improve the security of nuclear material in Russia.

Safeguards programs directed toward civil nuclear energy are spread over two agencies: the State Department and the Department of Energy, including its Office of Nuclear Energy Science and Technology and National Nuclear Security Administration.

Currently, what little safeguards R&D is being done is dispersed and the budget is less than \$5 million. The *total* annual safeguards budget includes both domestic and international programs that largely implement or transfer technologies that are the result of R&D carried out 10 to 20 years ago.

### **Proven Value**

Safeguards have been sufficiently effective to make theft and diversion from safeguarded facilities an unlikely path for proliferation in the past. Consequently, clandestine activities and covert facilities have become the more likely routes to obtaining nuclear materials. Even in such cases, technical safeguards including environmental sample analysis and surveillance analysis have proved effective.

Following the revelations about the Iraqi weapons program after the 1990 Gulf War, the technical safeguards of the IAEA were strengthened to include measures to improve the ability to detect undeclared activities.

In North Korea, environmental sampling helped to prove that North Korea was making false claims about its reprocessing activities. In Iran, disclosures by opposition groups supplemented by surveillance technology analysis and environmental sampling are revealing the status of Iran's nuclear program.

### **Safeguards Applications**

The various elements of nuclear power generation are depicted in Figure 1. The figure shows both the "open" fuel cycle in which spent fuel is stored as waste and the "closed" fuel cycle in which the spent fuel is chemically reprocessed, some of the fissile components recycled in reactors for further use, and the highly radioactive fission products transformed to high level waste for disposal in a geological repository.

Each fuel cycle facility type requires safeguards. Enrichment plants, fuel fabrication facilities, reactors, reprocessing plants, and waste storage sites must all be monitored and present technical safeguards challenges.<sup>20</sup>

### **Revitalizing Safeguard Research and Development**

Proliferators are adaptive. For technical safeguards to remain functional at containing *theft*, *diversion* and *breakout*, they must advance at least as quickly as a proliferator's techniques and potential opportunities.

Furthermore, technical advances provide opportunities to do more sophisticated and cost-effective monitoring. Technical safeguards must therefore be an ever-evolving response to proliferation challenges.

A robust safeguards R&D program is the single most significant technical investment that can be made to enhance the proliferation resistance of nuclear power in the near term. The investment in safeguards R&D will be most effective when coupled with changes in institutional arrangements, such as those that would limit the number of enrichment facilities.

As already noted, the potential growth of nuclear energy drives the need for greater efficiency to leverage limited inspection resources. Yet, the current federal safeguards program is primarily an implementation and technology transfer program and it must be enhanced to meet the challenge.

Figure 4 identifies some of the primary safeguard technical challenges.

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<sup>20</sup> For an introduction to these four technologies see: <http://eia.doe.gov/cneaf/nuclear/page/intro.html> For more technical background on these facilities: "Nuclear Energy : Principles, Practices, and Prospects" by D Bodansky, Springer, 1996.

### Safeguard Technical Objectives (Fig 4)

ENRICHMENT PLANTS	REACTORS AND FUEL FABRICATION	REPROCESSING PLANTS	WASTE SITES
<p>Detect concealed enrichment plants.</p> <p>Detect production of highly enriched uranium or excess amounts of low enriched uranium in declared plants.<sup>21</sup></p>	<p>Detect concealed production reactors</p> <p>Detect covert production of nuclear material.</p> <p>Uncover diversion of nuclear material from declared inventories.</p>	<p>Detect concealed reprocessing plants.</p> <p>Uncover undeclared use of facilities for separation or purification activities.</p> <p>Detect diversion of nuclear material.</p>	<p>Detect diversion of nuclear material or spent fuel.</p>

Key safeguards technologies to meet the detection objectives outlined in Figure 4 must be advanced to adequately limit the proliferation risks associated with the potential global expansion in nuclear power. However, the authors of this report learned in briefings from program directors at the State Department, the Department of Energy (DOE) and the National Nuclear Security Administration (NNSA) that there is no focused safeguards R&D budget or program providing a technology-base for nuclear materials security or international safeguards.

There *is* significant funding for technology transfer and implementation programs – most notably in the Cooperative Threat Reduction Program, the Material Protection, Control, and Accounting (MPC&A) program, and the Department of Homeland Security. However, for the most part, these programs rely on technology developed 20 years ago.

The urgent safeguards technology goals identified in Figure 4 will only be attained with a more structured and revitalized effort. The agencies participating in safeguard development should establish clear technology development goals for the next five years. For the longer term, a technology roadmap is needed to carry the program through subsequent stages of development. Such goals and roadmap will foster a consistent R&D base and help the US to promote the international importance of an enhanced technical safeguards agenda.

<sup>21</sup> HEU: uranium containing any mixture of the isotopes <sup>235</sup>U and/or <sup>233</sup>U such that  $(\%^{235}\text{U} + \frac{5}{3}\%^{233}\text{U}) \geq 20\%\text{U}$ ; LEU: enriched uranium containing lower amounts of <sup>235</sup>U and/or <sup>233</sup>U.

One office (NNSA/NN has the most appropriate technology and non-proliferation charter) should take the leadership role in coordinating an enhancement of the overall national safeguards R&D program. With a concentration of effort and appropriate management, it is possible that significant advances in safeguards technology can be achieved with modest increases in investment. At the same time, it is important to include the relevant experts in industry and the university communities.

### **Safeguard R&D Focus Areas**

Technological advancements are needed in all safeguards areas in order to achieve more direct monitoring of nuclear facilities, more sophisticated methods for the IAEA to detect undeclared nuclear activities, and more advanced surveillance.

Indeed, one research and development goal of technical safeguards should be to spur a transition from the current system of periodic inspections to a system of continuous remote monitoring. Such an evolution of technology could provide more timely detection, reduce personnel costs and dramatically improve the barriers to theft, diversion and breakout. Such advancements in safeguards technology offer the only practical way of realizing the ideal goal of monitoring nuclear programs “at all times at all places”.

Additional innovative safeguards technology paths should be explored such as, for example, the development of technology that can impede unauthorized operations. Such safeguards could be used to shut down a system or impede operation until help arrives in the event that a facility is violating operating agreements.

Specifically, nuclear security and international safeguards require improved:

- Detection methods including:
  - i. higher resolution, lighter weight, lower power, room-temperature radiation detectors;
  - ii. rapid, remote, tamper-resistant nuclear material item identifiers; and
  - iii. rapid, remote, unique, minimally intrusive personnel identifiers.
  - iv. fuel cycle facility process monitoring
  
- Quantitative assay methods for nuclear materials accounting including:
  - i. smaller, cheaper, more accurate, lower power, easier to calibrate and operate non-destructive assay systems for use throughout the fuel cycle; and
  - ii. faster, cheaper, environmental sample analysis.

- Systems integration including:
  - i. improved information-management and analysis tools for the IAEA for open source analysis and commercial satellite imagery analysis;
  - ii. integration of data from disparate sensor types and automated anomaly detection; and
  - iii. design optimization of safeguards systems.
  
- Effectiveness evaluation including determining the best combinations of proliferation-resistance measures to employ for particular fuel cycle facilities.

### **Field Testing Safeguards – Models of Proliferation Resistance**

Advanced safeguards technologies and systems must be field-tested if they are to perform reliably in fuel cycle facilities around the world. The R&D described above must be developed for use in real facilities and tested under conditions that are as representative as possible of the actual situations that the IAEA and national authorities face today and will encounter in the future. In some cases, this may require cooperative arrangements to work in operating commercial facilities in the US – where possible – or in foreign countries where such arrangements can be made. To maintain technical leadership, however, the United States needs to invest in representative test and evaluation facilities, such as making an enrichment facility at the Oak Ridge National Laboratory a model for technical safeguards. Noting the high cost of such facilities, consideration should be given to adapting the Fuel Material Examination Facility (FMEF) at Hanford for transuranic work. That facility was constructed to support the US fast breeder program that was terminated, and FMEF was never brought into operation.

New U.S. facilities should incorporate state-of-the-art safeguards systems developed in cooperation with the IAEA and thus serve as models to demonstrate to the international community advanced systems for IAEA safeguards. The new USEC Inc “lead cascade” at Portsmouth, Ohio and the proposed LES enrichment facility in New Mexico could provide near-term demonstrations and test beds for advanced centrifuge safeguards systems.<sup>22</sup>

### **International Collaborations**

International cooperation in nuclear security and international safeguards technology development should be given higher national priority. International cooperation to enhance IAEA safeguards has gone on for many years with a number of countries. For example, Japan has a long history of productive collaboration with U.S. national laboratories to develop and demonstrate advanced technologies for use by the IAEA. Giving the DOE and the State Department the

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<sup>22</sup> <http://www.nrc.gov/materials/fuel-cycle-fac/usecfacility.html>

flexibility to expand such technical collaborations, in particular in regions anticipating significant growth in nuclear energy, will contribute to both safeguards technology development and to its rapid adoption.

The goal of collaborative efforts should be to design safeguards directly into critical nuclear systems and sub-systems from the outset.

### Recommendations

- Significantly enhance the Technical Safeguards R&D program: increase resources, identify near-term technology goals, formulate a technology roadmap, and improve interagency coordination, and involve the commercial sector.
- Make future U.S. enrichment and/or reprocessing facilities models for proliferation resistance and technical safeguards.
- Expand efforts in international technical collaborations in safeguards R&D and pilot programs for advanced safeguards. A goal of the collaborations should be designing safeguards directly into critical nuclear systems.

## Section IV

# Long-Term Approaches for Enhancing Proliferation Resistance: New Nuclear Reactors & Fuel Cycles

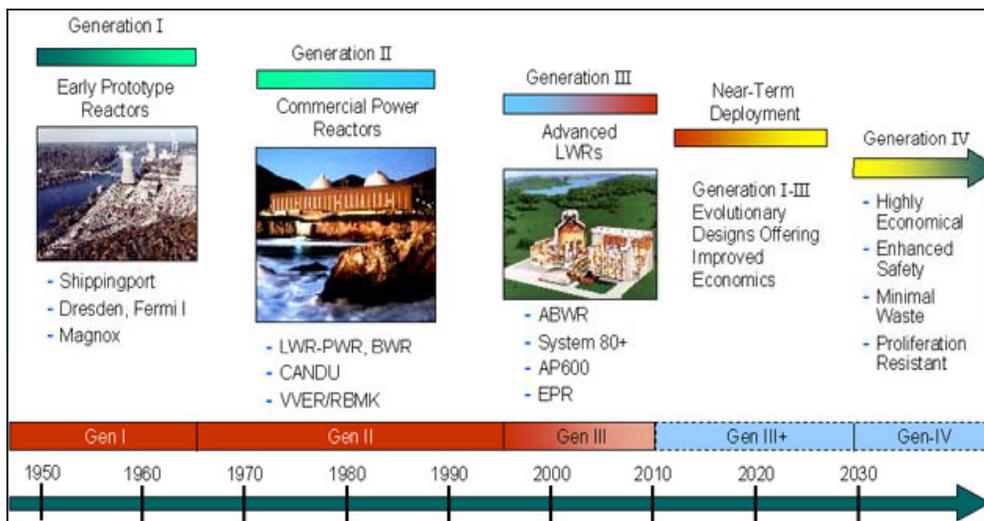
Nuclear systems design and development programs are long-term approaches to reducing proliferation risks. In general, the goal is to make future reactors and fuel cycles - 10 to 30 years from now - significantly more proliferation-resistant than current models and designs. The following sections examine these programs and provide recommendations that are intended to strengthen their contributions to enhancing proliferation resistance in the long-term.

### A. Generation Four Nuclear Energy Systems Initiative (Gen IV)

#### Reactor Design: History

The first fifty years of the 20<sup>th</sup> Century was a period of rapid advancement in understanding nuclear science and technology. It took only a decade to advance from the discovery of the neutron in 1932 - and just four years from the discovery of fission in 1938 - to the construction of the first crude nuclear “reactor” under the University of Chicago’s football stadium and the formation of the Manhattan Project that developed the first nuclear bomb.

The Evolution of Nuclear Power (Fig 5)<sup>23</sup>



<sup>23</sup> Department of Energy: <http://gen-iv.nc.doe.gov/>

In the 1950's, the first generation of civilian nuclear power reactors - Gen I – was constructed. Companies that developed the technologies for nuclear bomb production became leaders in the rapid expansion of nuclear energy into electrical energy production. In 1954, Congress amended the Atomic Energy Act of 1946 to permit civilian ownership of nuclear material to facilitate the expansion of civilian use of nuclear energy. Government development of nuclear energy included emphasis on reactors that used enrichment facilities that were also used for nuclear weapons.<sup>24</sup> The influence of government priorities was the primary reason that enrichment became integral to the development of commercial reactors.

In the US, companies such as General Electric and Westinghouse (key contractors in the government programs of the 1940s and 1950s) developed light water designs that now dominate the power reactor industry in the U.S. and in most other parts of the world. These power plant designs (Gen II) provide a significant fraction of the electricity supply in many markets worldwide. More advanced designs of these reactors (Gen III) have been approved by nuclear licensing authorities, deployed in a few locations, and are ready for widespread deployment.

Recently the U.S. and nine other countries - Argentina, Brazil, Canada, France, Japan, Republic of South Africa, Republic of Korea, Switzerland, and the United Kingdom - anticipating that the world may be entering a period of expansion of nuclear energy, have joined in a collaboration to develop another generation of more advanced nuclear power systems (Gen IV).

### **Proliferation Resistance & Gen IV Development**

The world and the U.S. may be entering a period of expansion of nuclear energy. International regimes to manage the new nuclear power systems have been proposed. President Bush has a two-part proposal involving fuel assurances and pledges to restrict sales.<sup>25</sup> IAEA director, Mohammed ElBaradei proposed a 5-year moratorium on construction of new enrichment and reprocessing plants while an effort is made to establish a multi-national alternative to nationally owned plants.<sup>26</sup>

In parallel with advancing new institutional structures, it remains important to assure that the proposed Gen IV technologies physically impede proliferation through all possible means. While cost and efficiency will dominate the interest of the commercial nuclear power sector in Gen IV decisions, the robustness of the non-proliferation regime will be a critical factor in sustaining support for nuclear energy in the decades ahead. Thus, future reactor design and development must reflect a high priority for proliferation resistance.<sup>27</sup> Recently, the countries participating in the Gen IV collaboration announced that six concepts would be pursued.<sup>28</sup> It is therefore urgent to establish shared priorities and constraints.

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<sup>24</sup> This facilitated the design of compact reactor for naval propulsion.

<sup>25</sup> President Bush, February 11, 2004: <http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html>

<sup>26</sup> [http://www.iaea.org/NewsCenter/News/2005/npt\\_2005.html](http://www.iaea.org/NewsCenter/News/2005/npt_2005.html)

<sup>27</sup> Designing the fuels so that the intervals between refuelings were extended from a year or two to more than a decade would, for example, reduce frequency of access to the reactor fuel.

<sup>28</sup> [http://www.energy.gov/engine/content.do?PUBLIC\\_ID=17543&BT\\_CODE=PR\\_PRESSELEASES&TT\\_CODE=PRESSRELEASE](http://www.energy.gov/engine/content.do?PUBLIC_ID=17543&BT_CODE=PR_PRESSELEASES&TT_CODE=PRESSRELEASE)

## **Proliferation-Resistance Criteria**

The Department of Energy is in the process of developing proliferation-resistance criteria through its Proliferation Resistance and Physical Protection (PR&PP) Assessment. A goal of PR&PP is to produce criteria that can be used to evaluate GEN IV designs. A further goal of the PR&PP process is to generate standards that lead to a consistent framework for proliferation resistance, similar to the framework that exists for safety.

At this time, a methodology for constructing the PR&PP criteria has been drafted. The next step is to test and refine the methodology with nuclear systems designers. The program has no definite milestones beyond FY '06.

It is possible that PR&PP criteria will not provide clear and unequivocal guidance, but it is important to test whether practical criteria can be developed across the spectrum of nuclear energy alternatives. Therefore, funding for PR&PP should be sustained and the involvement of nuclear reactor designers should be secured. To insure that it produces timely results, the DOE should also develop a timeline for the development of the intended proliferation-resistance framework.

Cost, safety, waste disposal, and proliferation resistance are all critical design issues for future nuclear systems. Yet, issues are typically prioritized in development of new technologies. Given the proliferation risks associated with the global expansion of nuclear energy, proliferation resistance should be a constraint on design and development of new systems.

Practically, this constraint means, for example, that Gen IV systems should be designed to fully integrate safeguard technologies that can continuously monitor and impede any misuse – advanced safeguards should be “built-in”. Processes, designs, and initiatives that might be attractive on the basis of cost, performance, and other considerations should not be pursued if they are not proliferation-resistant or should be modified to assure the strongest barriers to proliferation.

### **Recommendations**

- To support the development of practical proliferation resistance criteria that can lead to a consistent framework, the DOE should: maintain Proliferation Resistance and Physical Protection resources, secure nuclear reactor designers' involvement in the PR&PP assessment, and establish more detailed project timelines.
- Make proliferation resistance a constraint on future reactor design & development.

## **B. Fuel Cycle R&D**

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### **The Department of Energy Advanced Fuel Cycle Initiative Goals**

One of the Department of Energy's stated primary goals for its AFCI program is to develop spent fuel treatment technologies that would significantly delay or eliminate the need for more than one national nuclear waste repository. A further stated DOE goal is to research technologies that would support the development of a closed nuclear fuel cycle, thereby decreasing the amount and changing the character of the material needing long-term geological disposal.<sup>29</sup>

### **Waste Disposal & Reprocessing: Background**

Currently, spent fuel from U.S. nuclear power plants is stored on-site at the plants where it was produced. According to the plan laid out in the Nuclear Waste Policy Act of 1982 (NWPA), the Department of Energy (DOE) will remove this spent fuel from the plants and dispose of it in deep-geological repositories.<sup>30</sup> In 1987, the Congress amended the NWPA so that the first national repository would be built at Yucca Mountain, Nevada.<sup>31</sup>

The Yucca Mountain Repository is undergoing licensing challenges and at the very least it may be considerably delayed. Nevertheless, under current law, the Repository is limited to handling only a fraction of the waste that is expected to be generated by current US nuclear power plants.<sup>32</sup> Specifically, the Repository is limited to 70,000 metric tons of heavy metal [tHM] until a second repository has been put into operation.<sup>33</sup> Because 10 percent of this capacity is set aside for waste from the U.S. defense programs, only 63,000 tHM capacity is available for spent power-reactor fuel.<sup>34</sup> According to DOE projections, US reactors will have generated this amount of spent fuel by 2008. If, as currently expected, most US power reactors receive license extensions that allow them to operate until they are 60 years old, they will continue to discharge spent fuel at a rate of about 2,000 tHM per year until a total of 120,000-130,000 tHM has accumulated by around 2040. That is nearly twice the amount that is allowed to be disposed of at Yucca Mountain according to current law. However, the geological capacity of Yucca Mountain may be sufficient to hold it all.

The NWPA requires the Secretary of Energy to "report to the President and to Congress on or after January 1, 2007, but not later than January 1, 2010, on the need for a second repository."<sup>35</sup> Because the total amount of spent fuel from

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<sup>29</sup> A "closed cycle" is a nuclear system in which the spent fuel is reprocessed and its contained plutonium and perhaps other transuranic elements are recycled.

<sup>30</sup> NWPA, Sec. 302, a5B.

<sup>31</sup> NWPA, Sec. 160. The Nuclear Regulatory Commission (NRC) licensing process for the Yucca Mountain repository is on-going.

<sup>32</sup> Congressional testimony of Secretary of Energy Spencer Abraham, May 16, 2002.

<sup>33</sup> This includes both spent fuel and the radioactive waste from reprocessed spent fuel: NWPA, Sec 114, d.

<sup>34</sup> *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, [Final Yucca Mt EIS] DOE/EIS-0250, 2002, Summary, [http://www.ocrwm.doe.gov/documents/feis\\_2/summary/indexsum.htm](http://www.ocrwm.doe.gov/documents/feis_2/summary/indexsum.htm)*

<sup>35</sup> NWPA, Sec. 161.

currently operating U.S. reactors is projected to exceed the currently legislated 63,000-tHM quota for Yucca Mountain by 2008, the Secretary will have to recommend either:

- 1) That a second repository is required, or
- 2) That Congress increase the legal limit on the amount of radioactive waste that can be placed in the first repository, or
- 3) That Congress defer any decision for some period.

### **Potential Reprocessing Benefit: Reduce the Waste Burden**

Currently, the Department of Energy has no formal position about which of these options to recommend. But the desire to provide for the disposal of additional nuclear waste without building a new repository has led to a suggestion that reprocessing of nuclear waste could be used to reduce the quantity of nuclear material that would need to be disposed of at Yucca Mountain.

The Department of Energy responded to the reprocessing suggestion by shifting the emphasis of its Advanced Fuel Cycle Initiative (AFCI). In 2003, DOE reported to Congress that if spent fuel is reprocessed to remove the uranium and transuranic elements that it contains,<sup>36</sup> the Yucca Mountain repository might be able to hold the high-level waste from a much larger quantity of spent fuel and “potentially eliminate the technical requirement for a second [repository].”<sup>37</sup> The AFCI reprocessing program seeks to develop technical options to accomplish this.

The interplay between possible reprocessing strategies and high-level waste geological disposal is a complex one. The reduction of waste volume and mass are less important compared to other issues such as heat loads and surface storage times. And while such reprocessing strategies are important, they are not urgent.

### **Potential Reprocessing Risks: Proliferation & Nuclear Terrorism**

While the spread of centrifuge enrichment technology is currently considered to be the principal proliferation threat, the reprocessing of spent nuclear fuel has inherent

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<sup>36</sup> “Transuranics” are elements with atomic numbers greater than uranium, created by neutron capture by uranium isotopes, and subsequent neutron captures and other decays. In spent LWR fuel, the most important transuranics are neptunium, plutonium, americium, and curium.

<sup>37</sup> The uranium would be disposed of as low-level waste or recycled. The transuranics would be recycled and fissioned partially in current-generation light-water reactors and partially in future fast-neutron reactors. For details see: *Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research* (U.S. DOE, Office of Nuclear Energy, Science, and Technology, 2003, p. II-4.

Partial chemical separation of the 30-year half-life fission products, cesium-137 and strontium-90, and their storage on the surface until they decay, would increase the effective capacity of the repository still further. See: “Spent nuclear fuel separations and transmutation criteria for benefit to a geological repository,” by R. A. Wigeland, T.H. Bauer, T.H. Fanning, and E.E. Morris, Nuclear Engineering Division, Argonne National Laboratory, Waste Management 2004 Conference, Tucson, AZ, Feb. 29-March 4, 2004.

DOE is funding the development of spent-fuel reprocessing technologies that could accomplish the necessary separations of uranium, cesium with strontium, plutonium with technetium, and americium with curium: “Designing and demonstration of the UREX+ process using spent fuel” by G. F. Vandergrift *et al.*, Chemical Engineering Division, Argonne National Laboratory, Atlante Conference 2004, Nimes France, June 21-25, 2004.

proliferation risks.<sup>38</sup> Reprocessing using currently commercialized technologies leads to the generation of separated plutonium, which can be directly used to manufacture nuclear weapons.<sup>39</sup> Consequently, reprocessing technologies can create risks of *diversion*, *sale* and *breakout*. Where reprocessing involves the handling, transport, and storage of weapons-usable plutonium and fuels containing plutonium, there is an associated risk of *theft*.

Worldwide, about 240 declared tons of separated plutonium have been stockpiled as a result of civilian reprocessing programs, primarily in France, the United Kingdom, Russia and Japan. The stockpiles are still increasing.<sup>40</sup>

In countries with stable societies and high standards of security and accounting and personnel reliability, the risks of theft are less, though not negligible. Even in stable Britain, the Royal Society warned in 1998 that "the chance that the [British] stocks of plutonium might, at some stage, be accessed for illicit weapons production is of extreme concern."<sup>41</sup> Clearly, the dangers are higher in countries with low standards of security or high dangers of penetration by terrorists.

Currently, the US does not reprocess spent nuclear fuel.<sup>42</sup> In the absence of reprocessing, the stored spent fuel emits intense radiation from the long-lived fission products that are mixed with the other elements in the fuel. The radiation deters theft and makes separation of weapon-useable fissile materials difficult.<sup>43</sup> Indeed, unprocessed spent fuel can be a much more theft-resistant storage form for at least a century than reprocessed fuel which is protected only by the relatively weak radiation from the fissile material alone.<sup>44</sup>

The US adopted a no-reprocessing policy in the mid-1970s after India used plutonium separated for "peaceful purposes" to develop a nuclear explosive. Other countries, including Brazil, Pakistan, South Korea, and Taiwan, sought to follow India's example by launching "civilian" reprocessing programs. In each case,

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<sup>38</sup> It could also have significant negative effects on the economics of nuclear power. A French government commission concluded that if France ceased reprocessing in 2010, it will reduce the cost of nuclear electricity by about 0.5 mil per kw-hr or about 1% over the remaining lifetime of its current fleet of power reactors. See: *Economic Forecast Study of the Nuclear Power Option* (Planning Commission, Government of France, 2000); available at, Section 3.4 [http://fire.pppl.gov/eu\\_fr\\_fission\\_plan.pdf](http://fire.pppl.gov/eu_fr_fission_plan.pdf)

<sup>39</sup> "U.S. Fuel Cycle Policy," National Security Policy Directive 17 (2002).

<sup>40</sup> France, the United Kingdom, and Russia are already nuclear-weapon states and the United Kingdom has decided to end its reprocessing program, but Japan appears to be about to launch operations at a major new reprocessing plant.

<sup>41</sup> *Management of Separated Plutonium*, (London, The Royal Society, 1998) Summary.

<sup>42</sup> "U.S. Fuel Cycle Policy," National Security Policy Directive 17 (2002).

<sup>43</sup> Weapon-usable transuranics (primarily plutonium) are diluted by 100 times as much uranium in the spent fuel and protected by the intense gamma radiation generated by fission products. After ten years, this radiation comes primarily from cesium-137.

<sup>44</sup> "Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air" by W.R. Lloyd, M.K. Sheaffer and W.G. Sutcliffe (Livermore, UCRL-ID-115199, 1994).

Reprocessing removes nearly all of the fission products, greatly reducing the radiation field of the remaining weapon-usable transuranics. See Kang and von Hippel, "The limited non-proliferation benefits from recycling unseparated transuranics and rare-earth fission products from aged spent fuel," *Science & Global Security*, to be published.

The once-through fuel cycle leads to a continual buildup of the world's plutonium inventory that will not be as well "protected" by a high-radiation barrier after the fission products decay away.

however, the effort was halted, in large part because of US opposition. The United States questioned the motivation the countries had for acquiring these technologies and argued that its own example demonstrated that reprocessing is not required to have a robust nuclear-power program.

### **Balancing Benefits and Risks**

Any decision to reprocess spent fuel in the United States must balance the potential benefits against the proliferation risks.

Fortunately, there is no near-term urgency to make a decision on implementing reprocessing in the United States. No foreseeable expansion of nuclear power in the US will make a qualitative change to the need for spent fuel storage over the next few decades. Even though Yucca Mountain may be delayed considerably, interim storage of spent fuel in dry casks, either at current reactor sites, or at a few regional facilities, or at a single national facility, is safe and affordable for a period of at least 50 years.<sup>45</sup>

Further, any spent fuel that would be emplaced at Yucca Mountain would remain available for reprocessing for many decades. Nuclear Regulatory Commission regulations require that the Yucca Mountain repository, if licensed, remain open and the waste be retrievable for 50 years after emplacement of the waste. In the meantime, the repository would provide excellent protection of spent fuel from terrorist threats, and would be capable of serving as a final disposal solution if that is eventually judged to be appropriate.

The decision on a second repository – or on whether to reprocess - can therefore be comfortably deferred, and should be deferred, for at least a decade. The deferral allows for time to determine the best path for the next phase of the expansion of nuclear power, and for the handling of the spent fuel from the nation's reactors.<sup>46</sup> It is important, however, to use that time effectively to explore the options more thoroughly than has been done to date.

In the longer term, the balance among the benefits, costs, and risks of reprocessing may change significantly. By reprocessing spent fuel and burning the recovered uranium and plutonium in a nuclear "breeder" reactor, it is possible to get as much as 50 times more energy out of the original uranium. Therefore, if nuclear energy expands substantially in the future and puts pressures on the availability of low-cost uranium fuel,<sup>47</sup> then reprocessing and breeder reactors could become the preferred option if the associated proliferation risks can be addressed.

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<sup>45</sup> "Disposition of High-Level Waste & Spent Nuclear Fuel: Continuing Societal & Technical Challenges", NAS, 2001. There are important cost considerations as well. The costs of expanding Yucca Mountain or of developing a second repository are large, but the potential costs of a reprocessing program are likely to be larger. Not enough is known about any of these costs today to support a decision.

<sup>46</sup> NRC Commissioner Jeffrey Merrifield cautioned that new nuclear plants should be "evolutionary not revolutionary." NRC 17<sup>th</sup> Annual Regulatory Information Conference, March 8, 2005.

<sup>47</sup> This is unlikely to occur for at least a few decades: "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," M. Bunn, S. Fetter, J. P. Holdren & B. van der Zwaan, Nuclear Technology, Vol. 150, No. 3, June 2005.

Consequently, the AFCI research program should be maintained with an emphasis on enhancing both the proliferation resistance of the entire fuel cycle for each reactor-fuel-cycle concept being pursued and the technical support for new institutional arrangements for managing fuel cycle technology. By maintaining a program directed at fuel cycle research, the U.S. retains the ability to influence future directions, both technical and institutional, of the international community

Any reprocessing facility must be designed to be as proliferation-resistant as technically possible. At the same time, its operation must be sufficiently “transparent” that attempts to divert material or to operate it in a non-approved mode would quickly be detected by both the operators and multinational and international monitoring organizations. Several ideas for strengthening the proliferation resistance of such facilities are identified in a Report of the DOE’s Nuclear Energy Research Advisory Committee “TOPS” report.<sup>48</sup>

If such fuel cycle R&D is to have impact worldwide, it will be necessary to have a global program, involving all of the advanced nuclear countries. It is particularly important to involve the other permanent members of the United Nations Security Council: the United Kingdom, France, Russia, and China. China should be included for the additional reason that its plans for nuclear-power development exceed the expansion plans of any other country.

The participation of Russia is also vital. Currently Russia is not included in the U.S.-led “Generation IV” international study on the future of nuclear power because of U.S. opposition to Russia's nuclear cooperation with Iran.<sup>49</sup>

In the short term, it is understandable that considerations relating to the immediate crisis over Iran’s nuclear program should take precedence. However, the principal proliferation concern with Iran relates to centrifuges not associated with Russian cooperation and in the longer term, Russia cannot be left out of planning for a proliferation-resistant nuclear-energy future. Russia has enormous expertise in nuclear fuel-cycle technologies, is interested in marketing that expertise, and is the only country that is prepared to store spent fuel not only from countries to which it has supplied fresh fuel but also from third-party countries.<sup>50</sup>

In establishing any international fuel cycle R&D program, it is of overarching importance that the program itself not contribute to proliferation. This will require close collaboration between nuclear energy R&D and non-proliferation offices.

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<sup>48</sup> "Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems," Report by the TOPS Task Force of NERAC (October 2000).

<sup>49</sup> The US has refused to enter into the “Peaceful Uses of Atomic Energy” agreement with Russia as long as Russia cooperates with Iran.

<sup>50</sup> However, Russia has proposed this in the expectation that the spent fuel will eventually be reprocessed to provide startup cores for a new generation of fast-neutron breeder reactors.

## Recommendations

- There is no urgent need for the US to initiate reprocessing or to develop additional national repositories. DOE programs should be aligned accordingly: shift Advanced Fuel Cycle Initiative R&D away from an objective of laying the basis for a near-term reprocessing decision; increase support for proliferation-resistance R&D and technical support for institutional measures for the entire fuel cycle.
- If fuel-cycle R&D is to have impact worldwide, and if proliferation resistance norms are to be integral, it will be necessary to have a global program, including all of the advanced nuclear countries. It is particularly important to involve the other permanent members of the United Nations Security Council: the United Kingdom, France, Russia, and China.

## Appendix I:

# Glossary of Terms

**Actinide:** an element with atomic number of 89 (actinium) or above.

**Enriched uranium:** Uranium in which the proportion of U-235 (to U-238) has been increased above the natural 0.7%. Reactor-grade uranium is usually enriched to about 3.5% U-235, weapons-grade uranium is more than 90% U-235.

**Enrichment:** Physical process of increasing the proportion of U-235 to U-238.

**Fissile (of an isotope):** Capable of capturing a slow (thermal) neutron and undergoing nuclear fission, e.g. U-235, U-233, Pu-239.

**Fissionable (of an isotope):** Capable of undergoing fission.

**Fission:** The splitting of a heavy nucleus into two, accompanied by the release of a relatively large amount of energy and usually one or more neutrons. It may be spontaneous but usually is due to a nucleus absorbing a neutron and becoming unstable.

**Highly (or High)-enriched uranium (HEU):** Uranium enriched to at least 20% U-235. (That in weapons is about 90% U-235.)

**Low-enriched uranium:** Uranium enriched to less than 20% U-235. (That in power reactors is usually 3.5 - 5.0% U-235.)

**Reprocessing:** Chemical treatment of spent reactor fuel to separate uranium and plutonium from the small quantity of fission product waste products and transuranic elements, leaving a much reduced quantity of high-level waste. (cf Waste, HLW).

**Transuranic element:** A very heavy element formed artificially by neutron capture and possibly subsequent beta decay(s). Has a higher atomic number than uranium (92). All are radioactive. Neptunium, plutonium, americium and curium are the best-known.

**Uranium (U):** A mildly radioactive element with two isotopes that are fissile (U-235 and U-233). Uranium is the basic fuel of nuclear energy.

**Waste:**

**High-level waste (HLW)** is highly radioactive material arising from nuclear fission. It can be recovered from reprocessing spent fuel, though some countries regard spent fuel itself as HLW. It requires very careful handling, storage and disposal.

**Low-level waste (LLW)** is mildly radioactive material usually disposed of by incineration and burial.

## Appendix II

# Authors, Reviewers & Process

The authors and reviewers have a broad range of expertise. Together, they have considerable expertise in safeguards, nuclear-fuel cycle technologies, non-proliferation policy, international cooperation on nonproliferation R&D, and the management of federal nuclear technology programs.

The authors drew on their own expertise as well as briefings on December 16 and 17 at the American Physical Society office in Washington DC. Participants at the briefings included the managers and directors of the relevant S&T proliferation-resistance programs in the Department of Energy's Office of Nuclear Science and Technology and National Nuclear Security Administration, and the State Department.

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